LIFE CYCLE ASSESSMENT HANDBOOK

A Guide for Environmentally Sustainable Products

Mary Ann Curran, Editor

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Edited by

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Cincinnati, OH, USA

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Preface

For a growing number of companies, global diversity is a business imperative. Manufacturing operations have increasingly become technically and geographically diverse in the sourcing of resources, manufacturing and assembly operations, usage, and final disposal. This expansion, along with a growing awareness of sustainability and the responsibilities to the environmental, economic, and social dimensions that go with it, has prompted environmental managers and decision makers everywhere to look holistically, from cradle to grave, at products and services. The need for a tool that helps users obtain data and information to accurately and consistently measure the resource consumption and environmental aspects of their activities has never been more acute. Most importantly, people now realize that decisions should not lead to improving one part of the industrial system at the expense of another. In other words, the identification and avoidance of unintended consequences are essential in the decision making process. Out of this need came Life Cycle Assessment (LCA). What started as an approach to compare the environmental goodness (greenness) of products has developed into a standardized method for providing a sound scientific basis for product stewardship in industry and government. When used within an environmental sustainability framework, LCA ultimately helps to advance the sustainability of products and processes as well as promote society's economic and social activities.

When I set out to create the "latest and greatest" book on Life Cycle Assessment (LCA), I had three very specific goals in mind. First, I wanted it to be comprehensive, covering every possible facet of methodology and application. This was quite a challenge, given the ever-growing scope that LCA has reached over the years. As can be seen in the table of contents, the subject is addressed from a wide range of perspectives and in many applications. Note, however, that this book is not a "how to" manual with step-by-step instructions for conducting an LCA. Instead, I designed this book to explain what LCA is, and, just as importantly, what it is not. The immense popularity of the "life cycle" concept led to its use in a variety of assessment approaches, even in those approaches that are focused on a single environmental aspect. For example, LCA is often used in writing about carbon accounting. In these times of heightened concern over climate change, individuals and organizations alike are eager to measure the release and impact of greenhouse gases. But the results only address climate change and not the other equally important impacts. The exact meaning of the methodology is frequently misunderstood, resulting in carbon footprint and LCA being used synonymously, and incorrectly so. By narrowing an assessment to a single issue of concern, the results will not reflect the important benefit that LCA offers of identifying potential trade-offs. There are several other similar examples, which I will not go into here. I trust that after reading this book, the differences will be clearer.

Second, I wanted the reader to hear from the experts and leaders in LCA. I asked recognized LCA professionals for their contributions. I felt it was important to hear all the representative voices from industry, academia, and of course, the LCA consultants. We even heard from non-governmental organizations (NGOs). The book contains writings from 47 authors from 10 countries. Despite their busy schedules, all of the authors came through with marvelous contributions. I give my sincere thanks to the authors for their dedication and hard work and their willingness to take time away from their extremely busy careers and lives to share their experiences, wisdom, observations, and guidance which made this book possible (the term "herding cats" was used frequently as I waited for final manuscripts). In the end, I am extremely pleased with the outcome. There is much the reader can learn by drawing from the wealth of experience and knowledge that is contained within the covers of this book.

Third, I wanted to capture the latest advancements in LCA methodology and application in one convenient place. I also wanted to indicate where further advancement in LCA is still needed. The book was designed with a particular flow in mind. It begins at the beginning, with an historical account of LCA and how it has developed over the years. The following chapters cover the basics of the LCA methodology, and discuss goal and scope definition, inventory analysis, impact assessment, and interpretation. Then, multiple examples of application are presented. This is followed by aspects of how LCA is used in decision making, and how it is now evolving as the underlying principle behind environmental sustainability. The book is best approached from beginning to end, as each chapter was designed to build on the last. However, each chapter is self-contained, and readers may benefit from skipping to the topic(s) of interest to them.

LCA and LCA-based tools give us a way to improve our understanding of the environmental impacts associated with product and process systems in order to support decision making and achieve sustainability goals. In the early 1990s (before the first ISO 14000 series on LCA was established), there was considerable confusion regarding how LCA should be conducted. Even the term itself was debated, and 'life cycle analysis' and 'life cycle assessment' were used interchangeably. Eventually, 'assessment' became the preferred choice in the ISO standards and within the LCA community. 'Analysis' is still used by some (usually those who are less familiar with LCA), but I asked the authors to use 'assessment' throughout their writing to be consistent with the ISO standard, and to appease me. Over the last 22 years, it has been fascinating to watch the evolution of LCA practice, from concept to standardized methodology and on to being the 'backbone' of sustainability.

I intend for this book to be a useful reference tool for a wide audience, including students in environmental studies, government policy makers, product designers and manufacturers, and environmental management professionals. That is, I hope it is useful to anyone who wants to implement a life cycle approach in their organization, be it in the private sector or public, as well as those who simply wish to have a better understanding of what all the fuss over LCA has been about.

Cincinnati, Ohio, USA | Mary Ann Curran
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Environmental Life Cycle Assessment: Background and Perspective

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Abstract
Life Cycle Assessment (LCA) has developed into a major tool for sustainability decision support. Its relevance is yet to be judged in terms of the quality of the support it provides: does it give the information as required, or could it do a better job? This depends very much on the questions to be answered. The starting point was the application to relatively simple choices, such as making technical changes in products and choosing one material over another, with packaging as a main example. This was then followed by the use of LCA in consumer choices. Over time, there has been a shift to more encompassing questions, such as the attractiveness of biofuels and the relevance of lifestyle changes. This chapter describes the ongoing discussions on issues that still need to be addressed, such as allocation, substitution data selection, time horizon, attributional versus consequential, rebound mechanisms, and so forth. The chapter then describes how LCA might develop in the future. There are important tasks ahead for the LCA community.

Keywords: Life cycle assessment, LCA, allocation, attributional, consequential, decision support

1.1 Historical Roots of Life Cycle Assessment

The concept of exploring the life cycle of a product or function initially developed in the United States in the Fifties and Sixties within the realm of public purchasing. Back then, use cost often carried the main share of the total cost. A first mention of the life cycle concept, by that name, is by Novick (1959) in a report by the RAND Corporation, focusing on *Life Cycle Analysis* of cost. Costs of weapon systems, a main application at that time, include not only the purchasing cost, or only the use cost. They also cover the cost of

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development and the cost of end-of-life operations. Life Cycle Analysis (not yet referred to as 'Assessment') became the tool for improved budget management, linking functionality to total cost of ownership. This was a first for government. Method issues and standardization questions soon followed. How should data on past performance be related to expected future performance? How is functionality defined? Can smaller systems like jet engines be taken out of overall airplane functioning? Should system boundaries encompass activities such as transport? How should accidents and mistakes be considered? How should overhead costs and multi-function processes be allocated? For public budget analysis, the life cycle approach led to general questions on methodology and standardization, as in Marks & Massey (1971), also linking to other "life cycle-like' tools for analysis, especially cost-benefit analysis.

The life cycle concept rapidly spread to the private sector where firms struggled with similar questions. By 1985, a survey paper (Gupta & Chow, 1985) showed over six hundred explicit life cycle studies that had been published, all focusing on relating system cost to functionality. The methodology issues were treated in an operational manner, for example by Dhillon (1989). Optimizing system development and system performance became a core goal for the now broadly applied public and private life cycle analysis of cost.

There is now over a half a century of experience with function-based life cycle analysis of system costs, see the survey in Huppes *et al.* (2004), continuing in parallel with environmental Life Cycle Assessment, or environmental LCA (moving now from 'Analysis' to 'Assessment'), and later to the life cycle concept related to Life Cycle Costing (LCC). Returning to these roots might be an interesting endeavor.

1.2 Environmental Life Cycle Concepts

This life cycle concept was already fully developed when environmental policy became a major issue in all industrialized societies, at the end of the Sixties and in the early Seventies. Environmental policies, mainly command-and-control type, were at first source-oriented with very substantial reductions in emissions being realized. It soon became clear that such end-of-pipe measures were increasingly expensive. However, other options were not easily introduced into the mainly command-and-control type regulatory framework as it had been developed. Shifts in mode of transport, for example, were clearly of broad environmental importance, but not easily brought into the regulations. The comparative analysis of such different techniques for a similar function was hardly developed in a practical way. Cost-Benefit Analysis (CBA), as an example, was focused at projects that aim to maximize welfare. It was made obligatory for environmental regulatory programs in the US, starting in 1971 with Executive Order 20503, on Quality of Life. Adapted substantially by consecutive US presidents, it still is a main contender for environmental LCA in the public domain applications, and increasingly so in the European Union (EU) as well. Environmental LCA first developed relatively unobserved by the private sector, before having the name shortened to simply "LCA" at the end of the Eighties. Both CBA and LCA have a life cycle concept at their core. The major difference between them is that CBA specifies activities in time and then uses a discounting method, in line with dominant modes of economic analysis, which is similar to the Life Cycle Analysis of cost. LCA, on the other hand, uses a timeless steady-state type of system analysis, without discounting effects. CBA also quantifies environmental effects in economic terms and then discounts them. In modeling welfare effects of climate policies, for example, the discounting mode is dominant. That dynamic analysis seems superior to the static GWP (Global Warming Potential) analysis used in LCA. How to quantify environmental effects in an economic sense and how to discount effects spread across time remains a core issue in CBA, open to further public and scientific debate. In LCA the time frame discussion is hardly present. Looped processes are not, and cannot, be specified in time. The only explicit treatment of time is found in the consideration of the different environmental themes in GWP impacts, with scores being limited to 20, 50 or 100 years, and in the toxic effects of heavy metals and the like that are assumed to extend virtually to eternity. The time frame discussion, then, might be part of Interpretation, which is problematic in itself while also hardly any guidance is given in the ISO standards or in any of the instructional guides that followed.

It would be interesting to have a discourse on overlapping issues and strategic choices in the domains of Cost-Benefit Analysis; Life Cycle Analysis of costs; and environmental Life Cycle Assessment.

1.3 LCA Links to Environmental Policy

The conceptual jump from life cycle cost analysis to the first life cycle-based waste and energy analysis, and then to the broader environmental LCA (how we view LCA today) was made through a series of small steps. Documented history starts with the famous Coca Cola study from 1969, see Hunt and Franklin (1996), who were involved in LCA right from that start. The environmental focus was on resource use and waste management, not yet the broad environmental aspects that are usual in LCA now. The broad conceptual jump to environmental LCA as contrasted with Life Cycle Analysis of cost was made in the Eighties and formalized in the Nineties with the work of SETAC and the standardization in the 14040 Series of ISO, see Klöpffer (2006). From the start with the RAND Corporation in the end of the Fifties, the system to be analyzed was clear. It should cover the supply chain, including research and development, the use stage, and the processing of wastes from all stages, including end-of-life of the product analyzed.

The link to public policy was made based on concepts first developed in the Netherlands, in the Eighties at the Department of Environmental

Management headed by Pieter Winsemius. After the first stage of environmental policy, with command-and-control instruments directed at main sources, there was a shift to a systems view, and to a more general formulation of environmental policy goals in the Dutch Environmental Policy Plans, see also Winsemius (1990, original 1986). This shift from a source-oriented to an effect-oriented approach created a domain for environmental LCA from an environmental policy point of view, as contrasted to a business long-term cost view or a consumer interest point of view. Winsemius coined the environmental themes approach now dominant in LCA, looking for integration over the environmental compartments policies regarding water, air and soil. His overall policy strategy was based on now familiar themes: Acidification; eutrophication; diffusion of (toxic) substances; disposal of waste; and disturbance (including noise, odour, and local-only air pollution). Somewhat later, further national policy themes were added: climate change; dehydration; and squandering.

The theme-oriented policy formed the basis for a broadened view on environmental policy, now covering complementary entries like volume policy, product policy and substance policy. In their implementation it was no longer only chimneys and sewers but also people and organisations: the target groups of environmental policy, several groups of producers and consumers. The responsibility for consequences of actions shifted to these target groups, which had to internalise the goals of environmental policy as specified using the themes approach. If, how, and why this internalization happened is a subject of much debate; see de Roo (2003) for a first analysis. For doing so, the new metrics of the themes were most appropriate, indicating the environmental performance of business and consumers in a unified collective framework, that of (generalized) public environmental policy. Private organizations may have ideas on what themes should constitute the impact assessment. It is the collective point of view that creates the relevance of LCA outcomes. The themes approach remained specifically Dutch for a short while only. It inspired environmental policy of the EU; see the historic survey by Liefferink (1997). It was incorporated in LCA in an operational manner beginning in the Nineties, as the Life Cycle Impact Assessment method now dominant in LCA, of course with additions and adaptations. In the US the themes approach was not dominant in environmental policy, with more emphasis there on CBA. That probably was the reason that the introduction of the themes approach in environmental LCA followed later there.

It is an open question now if and how Life Cycle Impact Assessment can be linked to environmental themes as goals of public policy. These goals might be – but need not be – the goals of a specific country or of the EU. Public policy goals set as targets, for example as emission reduction targets for a substance, lack the integrative power of the themes approach. Goals set as general welfare maximation lack the link to specific domains of action. Themes can make the link. Also because product systems and LCA increasingly become global, passing the policy goals of specific countries, the foundations for the themes in LCA impact assessment should be clarified.

1.4 Micro Applications of LCA Rising

The last decades have seen a startling rise in the production of LCAs. There are consultants in virtually all countries, many with an international orientation. Databases and software have become widely available. There also are interesting in-firm developments. Two Netherlands-based firms we happen to know have their internal LCA capacity well developed, Philips and Unilever. Procter and Gamble contributes a chapter to this book on their LCA operations. The Unilever example is enlightening. They regularly produce internal LCAs on virtually all of their products, having produced well over a thousand LCAs by now. They use the LCAs for product system improvement, reducing easily avoidable impacts. These may seem tiny per product, but may be substantial from a dynamic improvement point of view. Tea bags used to have zinc plated iron staples to connect the bag and the carton handle to the connecting thread. This gave a dominant contribution to the overall life cycle impact of the tea bag system. The staples were first replaced by a glue connection and in many cases now by a sewing connection. Such product system improvement forms the core of LCA use. However, when having so many equivalent LCAs, new more strategic applications become possible. Can strategies be developed to reduce environmental impact covering more than one product, with more general guidelines for product development? Such applications are now developing in Unilever, see the box. Similarly, Philips has developed strategic guidelines at an operational level regarding the use of materials, reducing the number in each product and phasing out those with the largest contribution to environmental impacts.

LCA, in its micro level application, is now a two decade-old success story. With all caveats following, we should not throw out the baby with the bath water. LCA is here to stay, and the child is still growing.

1.5 The Micro-Macro Divide

The core goal of environmental LCA as was established in the Nineties was to help improve environmental quality, with product policy – internalized, private, and also in public regulations – as one entry into environmental policy. That role is based on the assumption that improved micro environmental performance of a product-function system corresponds to an environmental improvement at the macro level. That macro level in principle is global society at large in its environmental impacts, as product systems increasingly span the world. When looking at the mechanisms that link shifts or developments in micro level behavior to macro level performance it is perfectly clear that there is no direct correspondence. Cycling as mode of transport has a minor fraction of the impacts of car transport per kilometer traveled, but also has a minor fraction of the costs. Some elements of this discrepancy may be covered by eco-efficiency analysis of these transport systems, expressing environmental impacts not per functional unit but per Euro spent. Such micro level scores don't tell what the ultimate outcome of a shift to cycling in commuting will be. The income not spent on cars will be spent on something else, anything. The shift to cycling is also linked to a different spatial infrastructure, with different retail systems, different housing requirements, etc. Though one may be confident that this is all to the environmental good – there may be good reasons to believe so – that assessment is not just based on LCA. The analysis of the overall system effect can easily be set up in a way that cycling really is bad. If the income not spent on cars is assumed to be spent to a substantial degree on flight based holidays, the net environmental outcome of more cycling might well be negative. When reckoning with such behavioral mechanisms, the choice of mechanism will determine the outcome, quite haphazardly at the moment. So the question is if a strategy for analysis can be set up to include the most relevant mechanisms in an equitable way. The move towards consequential LCA is a possible step, but not the only one.

A core question is if dynamic, non-linear mechanisms can be incorporated in the comparative static or steady state framework of LCA, as consequential LCA. Or, should the micro level LCA technology system better be placed in a broader modeling system reckoning with income effects, dynamic market mechanisms, structural effects and constraints, and what more might be relevant? The modeling required definitely does not fit in the linear homogenous system of LCA based on matrix inversion for easy solutions. It seems wise to first investigate divergent cases with an open mind as to most relevant causalities, and to look into options for structured modeling later. Then a choice for micro-type consequential LCA might be substantiated, or not, or only for some applications.

1.6 Macro Level LCA for Policy Support

The use of LCA in public policy has been coming up, with an LCA-type of analysis being used. The domain of application of LCA has been that of specific product choices. However, the link to broader policy issues, never absent, seems on the rise. Biofuel, see below, is a major example, with unresolved discussion in the EU. The general feature of policy applications is that they should show how a change considered would work out, requiring an ex ante analysis of consequences of policy options, or an ex post analysis showing how a policy has worked out. In both cases we need to know 'how the world would have been different.' The functional unit with an arbitrary volume then is to be replaced by an analysis covering the total volumes. Policies tend to be set up in order to reach specified goals, not marginal effects of an unknown volume. Using traditional arbitrary-unit LCA for policy support assumes a correspondence between micro level LCA outcomes and macro level consequences for the choice at hand. This assumption should be substantiated. It also relates to the average versus marginal discussion, with causalities most easily established at a marginal level, but overall effects then requiring integration over all marginal changes, as increments. For substantiating the consequences of the policy choice at hand, the technical relations as covered in LCA should be part of the analysis, but also the broader behavioral mechanisms should be covered. If all mechanisms together come out negative, showing a rebound, simple LCA would have given the wrong advice.

A first step for the analysis is to place the choice in a framework of totals for society. Input-output analysis with environmental extensions can be set up in an LCA-type manner, with some details added to better cover the choice at hand. This hybrid analysis has come up as a theoretical tool, with one application related to the option of using fuel cell buses in urban transport, see Cantono *et al.* (2008). In the old Life Cycle Analysis of cost, the same link to input-output analysis was pointed out previously, see Staubus (1971). This IO framework allows one to specify one first secondary effect, the income effect. The higher cost of fuel cell buses replacing Diesel buses implies lower spending on other items, with lower environmental impacts there. However, this IO-analysis is static and cannot cover well broader causal mechanisms. Causal analysis can only be specified in time. It is the *before-after* analysis, of the situations *with-and-without* specific alternative policies. So the second step involves a dynamic analysis, of all mechanisms leading to the overall, the macro level, consequences.

The conclusion is that for supporting policy choices with macro level consequences the arbitrary functional unit based LCA will often be too narrow to give valid answers. A broader framework for analysis is then required.

1.7 Example Biofuels

In the biofuels discussion, all levels of questions come up. They range from small-step improvement options for a given biotechnology to produce biofuels; to the comparison between different fuels, including biofuels; and to an evaluation of a global shift towards a more biobased energy system. When looking at a small system, one may assume the changes to be so small that indirect effects are negligible. But the sum of all these small changes adds up to a substantial change. A small change in biomass demand for energy will have a small effect on biomass production and a small effect on energy prices. However, such effects are additive, and often non-linearly increasing. If biofuel is relevant, it has to be produced in substantial amounts. This also holds for the minor improvement in biotechnology. So, indirect effects cannot be ignored. A next option for simplified analysis is the assumption that all mechanisms not covered remain equal or do not influence the outcome. Both assumptions generally are not true in the case of bio-energy, see the OECD (Organization for Economic Cooperation and Development) study by Doornbosch and Steenblik (2008). These should be investigated empirically. A final option is to make assumptions on the rest of the world. One may assume, for example, that all additional biomass will come from barren lands not fit for food producing agriculture. This assumption is often present in studies on second and third generation biofuels. However, the use of fertile grounds will mostly be cheaper than barren grounds to produce biomass – that is why they were barren. In general, no mechanism exists to restrict biomass production for fuel to barren lands only. Therefore, to develop sound advice on biofuel choices we have to be comprehensive and cover 'all relevant mechanisms.'

What might these relevant mechanisms be for biofuels? A first set of mechanisms relates to the markets more or less directly involved. In the US case of corn based ethanol (first generation) or stover-based ethanol (second generation), this involves the fodder and food markets for these products. Directly connected are other products for these markets, especially wheat. Also directly linked are changes in land use, more corn and wheat pressing out other staple products like soy beans, increasing the price of soy beans a well. These three staple crops function on global markets, so even if the bioethanol is US-produced the effects are really global, in principle affecting all crops globally. The overall agricultural effect will include somewhat higher prices, an intensification of agriculture, with also higher nitrous oxides emission affecting climate, and an increase in the volume of agricultural land use. Two studies have investigated the impact on additionally induced conversion of tropical rainforest into agricultural land; see Searchinger *et al.* (2008) and Fargione *et al.* (2008). These two studies differ in set-up and outcomes and cannot directly be connected to LCA-type studies. They show however that such global effects of biofuel production cannot be neglected. One mechanism not covered by these studies is a feedback in spatial policy as has taken place in Brazil and Indonesia, with strengthened legislation and strengthened power in implementation. This administrative reaction to US, and similar EU, biofuel policy will of course have longer term effects mainly. Some of these issues will be treated in a bit more detail by Guinée in a later chapter, as the framework for Life Cycle based Sustainability Analysis (LCSA).

So here we are, with old-fashioned types of LCA studies showing how attractive biofuels may be, and a range of induced mechanisms often being detrimental in an environmental sense, both on the shorter, longer and very long term. What to do? The only answer seems to be: get on the job, make a framework for analysis, start filling in the framework with conceptual models, and produce first order quantifications on environmental outcomes. On the way to specifying the mechanisms involved one will encounter major social effects as well, with rising food prices in cities (with riots and possibly a major effect on the uprisings in the Middle East) and with rising agricultural incomes all over the world, also for the poorest farmers. How to come to an overall evaluation of several divergent effects spread out in time will be a next problem to solve, involving all problems that have already been encountered in Cost Benefit Analysis, but often have not been not solved adequately yet.

1.8 Why Environmental LCA?

The early development of cost-oriented LCA had clear goals: reducing cost while improving performance. That driver remains, with cost analysis an essential element in management accounting.